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A fiberoptic-coupled radiation dose verification system for prostate radiotherapy has been built and tested under clinical conditions using solid water phantoms. The dimensions of the radiation sensitive portion of the fiberoptic probe are 1-mm by 0.4-mm in diameter, providing unsurpassed spatial resolution for radiotherapy applications. The flexible fiberoptic probe is compatible with use in a medical catheter to provide in vivo monitoring capabilities. The use of fiberoptic bundles to replace discrete optical elements has resulted in a cost-savings of several thousands of dollars while increasing the reliability of the system. The system has very good sensitivity for all doses and dose - rates encountered in typical external beam radiotherapy procedures. The system exhibits exceptional linearity and has a reproducibility of better than 2% over a wide range of accumulated doses.

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INTRODUCTION:

The goal of this project is to develop an effective, multi-channel fiber-optic, in vivo radiation dosimeter to provide real-time feedback to physicians during the course of prostate radiotherapy treatments. It is expected that the device will provide physicians with better control of the delivered doses and improved targeting of the prostate gland. The device should lead to improved treatment protocols that will result in reduced morbidity and fewer undesirable side effects such as incontinence that often occurs following treatment due to accidental injury to the bowel, urethra and bladder.

BODY:

Task 1: Develop a patient dosimetry system using catheterized fiberoptic glass dosimeters and a laser readout unit suitable for clinical studies.

- **Manufacture glass fiber dosimeters and attach them to commercial fiberoptic cables.**
- **Adapt fiberoptic dosimeter for use with standard medical catheters.**
- **Design and manufacture a laser-based optical readout system.**

All elements associated with Task 1 have been successfully completed.

A 1-meter long, 20-mm diameter fused quartz rod was doped with copper ions using a patented (ref), high-temperature thermal diffusion technique. First, a copper ion source was prepared by impregnating porous Vycor glass (Corning 7940) with a saturated aqueous copper sulfate solution. This glass was dried and then heated to a temperature of 1150 C for a period of 4 hours. The glass was then pulverized to produce a glass powder that had the consistency of play-sand and had a light brownish green color.

The 1-meter long, 20-mm diameter fused quartz rod was placed inside of a 28-mm diameter fused quartz tube and the copper-doped Vycor powder was packed around the rod. The entire assembly was placed in a tube furnace and heated to 1150 C for a period of 48 hours. After cooling, the rod was removed from the tube and examined using a 266-nm ultra-violet light source. UV illumination of the copper-doped fused quartz rod resulted in a characteristic blue-green luminescence that is associated with emission from Cu^{+1} ions.

The 1-meter long, copper-doped fused quartz rod was sent to Fiber Guide Industries and was drawn into approximately 1 kilometer of 0.4-mm diameter optical fiber. The fiber had a silicone cladding and a nylon jacket for added strength.

Fiber dosimeters were manufactured by first cutting approximately 6 inch lengths of the copper-doped fiber and then stripping away the jacket and cladding. One end of the doped fiber was cleaved to produce a clean, flat surface that could be spliced to a similar sized, commercial optical fiber cable. The doped fiber was joined to the fiber cable using

a commercial fusion splicer. The two fibers were placed end-to-end between two electrodes that, when energized, served to melt the glass fiber ends allowing the two pieces of fiber to be fused into a single fiber. A UV lamp was used to delineate the copper-doped portion of the fiber and the fiber was cleaved to yield a 1-mm length of doped material attached to the fiberoptic cable.

The commercial fiberoptic cables that were used to fabricate the dosimeter probes consisted of a 0.4-mm diameter silica core with a silicone cladding. A black Tefzel (Teflon-like) jacket surrounded the fiber assembly. The result was a very flexible, 0.60-mm diameter probe that could be easily inserted into a traditional medical catheter. Figure 1 shows a photograph of a typical 1-meter long fiber dosimeter probe.

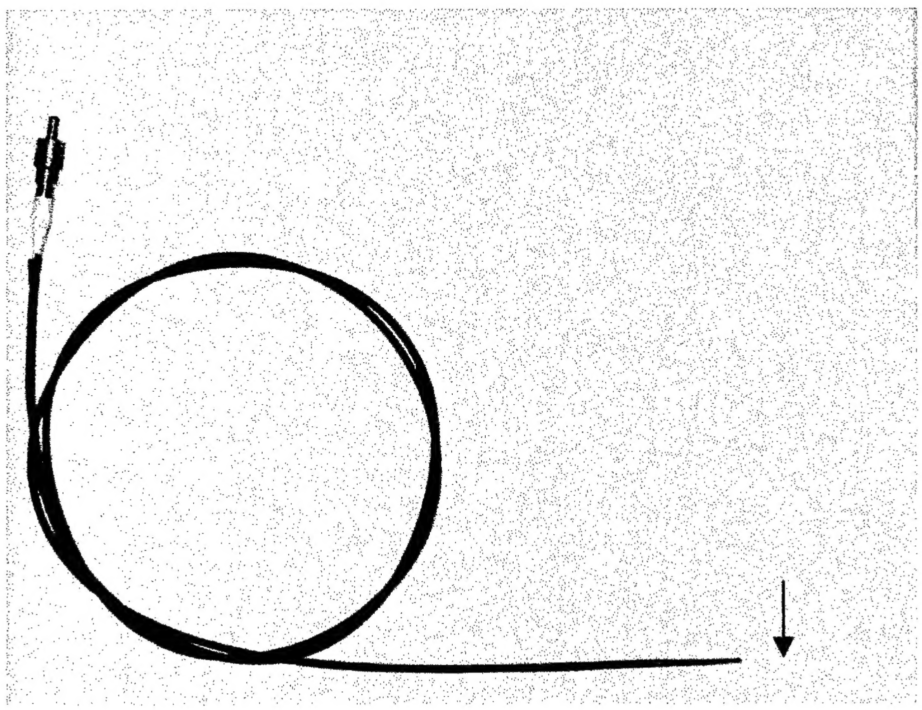

Figure 1. Photograph of the fiber dosimeter probe. The arrow indicates the position of the 1-mm long, copper-doped silica glass fiber.

Laser-Based Optical Readout Unit:

Considerable progress has been made on the design of the readout unit for the fiber dosimeter. A schematic of the unit is shown in Figure 2. The unit is capable of operating seven channels simultaneously, although only four channels are presently being used. The output of a fiberoptic-coupled, 1.2-Watt GaAlAs diode laser is filtered with a combination color glass/interference filter to remove residual light wavelengths below 780 nm. The filtered laser light is directed into a fiberoptic bundle that consists of seven individual fibers. Each of the seven fibers is directed to a separate dosimeter channel. The laser light is directed to the dosimeter probes using 10-meter lengths of fiberoptic

cable. In this way, the dosimeter readout unit can be operated from the control room, well away from the radiation source. The optically stimulated luminescence signal from the tip of each dosimeter probe is directed back through the fiber and back into the fiber bundle assembly. Six of the seven fibers that make up the bundle are used to direct the signal light to a photomultiplier tube detector (photon counting module PCM). The intensity of the signal light measured with the PCM is proportional to the absorbed radiation dose.

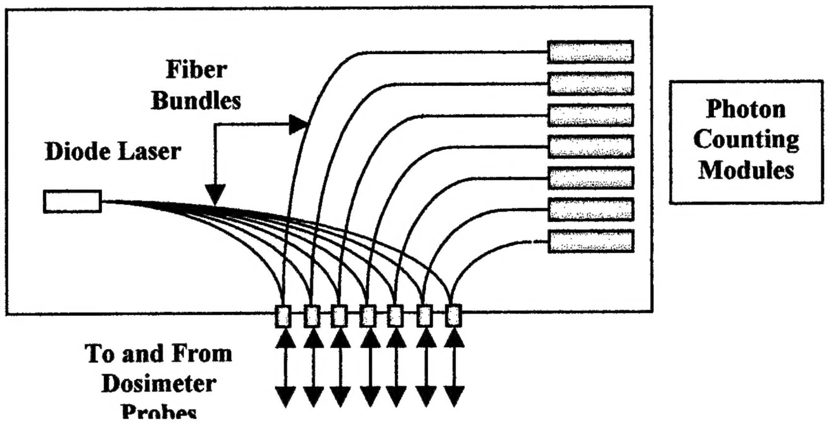

Figure 2. Schematic of the all-fiber optical readout unit.

Earlier versions of the fiberoptic-coupled dosimeter used discrete mirrors and lenses to direct the laser and signal light beams. The present version uses a fiber bundle approach that eliminates at least 2 mirrors, 2 lenses and a dichroic beam splitter per operating channel. For a multi-channel device, the fiber bundle design provides significant cost savings. For example, Mirrors and lenses cost approximately \$50 each and must be mounted in adjustable holders that cost an additional \$50 to \$150 each and a dichroic beam splitter costs approximately \$150. A seven-channel device would require 7 beam splitters, 14 lenses, 14 mirrors and 35 mounts, or approximately \$5950 of optical components. The seven-channel fiber bundle was purchased for \$1614. The all-fiber system does not require any adjustments, it is simpler, more reliable and robust than a discrete optics system. The fiber bundle is approximately 1/3 less efficient at collecting signal light as the discrete optics approach, but the observed signal levels obtained under clinical conditions are more than sufficient to provide excellent signal-to-noise.

The unit described above can also be used in a continuous, real-time mode in which the x-ray induced scintillation light is monitored. In this mode of operation, there is no need for the laser stimulation source. Depending on the nature of the procedure, either one or both modes of operation may be used. Figure 3 shows a plot of the signals obtained using the real-time and the OSL modes of operation.

An eight-channel RS232 PCI card was purchased to provide computer control of multiple channels. A Windows-based software program (LabView) has been written that allows for simultaneous monitoring of up to eight channels. The program provides information concerning the instantaneous dose rate, the average dose rate and the accumulated dose.

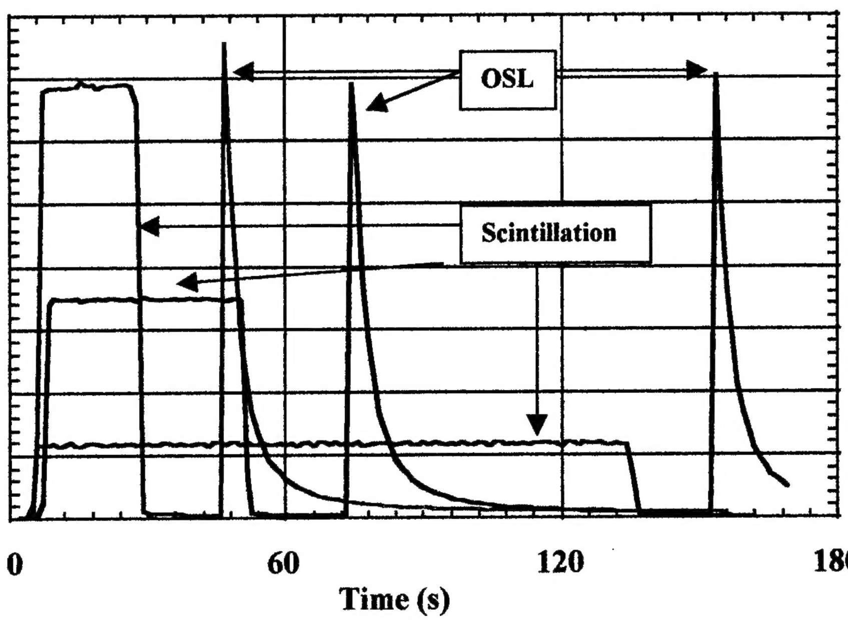

Figure 3. Signals recorded using the fiberoptic dosimeter system. The flat-line data represents signals recorded in real-time using the scintillation mode for dose rates of 100, 300 and 500 cGy/min. The sharply peaked data corresponds to the optically stimulated luminescence signals that were obtained approximately 20 seconds following the exposure.

The data is displayed in real-time numerically, and graphically. Threshold levels can be set for each channel that when reached, set off an alarm to warn of possible over exposure. The data is written directly to a standard spreadsheet format for documentation purposes. Figure 4 shows the LabView control screen.

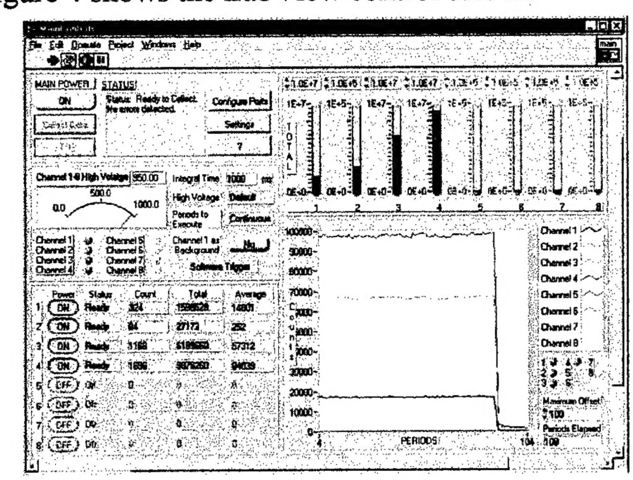

Figure 4. LabView control panel designed to monitor four fiber-coupled dosimeters simultaneously. Display provides information on the instantaneous count, the totalcounts and the average counts. Counts are related to absorbed dose by a proportionality factor.

Task 2: Perform clinical studies using the dosimetry system completed in Task 1.

- **Study characteristics of the system using tissue equivalent phantoms.**
- **Perform dose verification on ~20 patients receiving prostate beam therapy treatments.**
- **Assess the utility of the system.**

Extensive experiments were performed at the National Cancer Institute to characterize the performance of the fiber-optic dosimeter under clinical conditions. All studies to date have been conducted on tissue equivalent phantoms using a Varian, Clinac 60, 6 MeV x-ray treatment machine. For most measurements, the dosimeters were placed below 5-cm thick solid water phantoms.

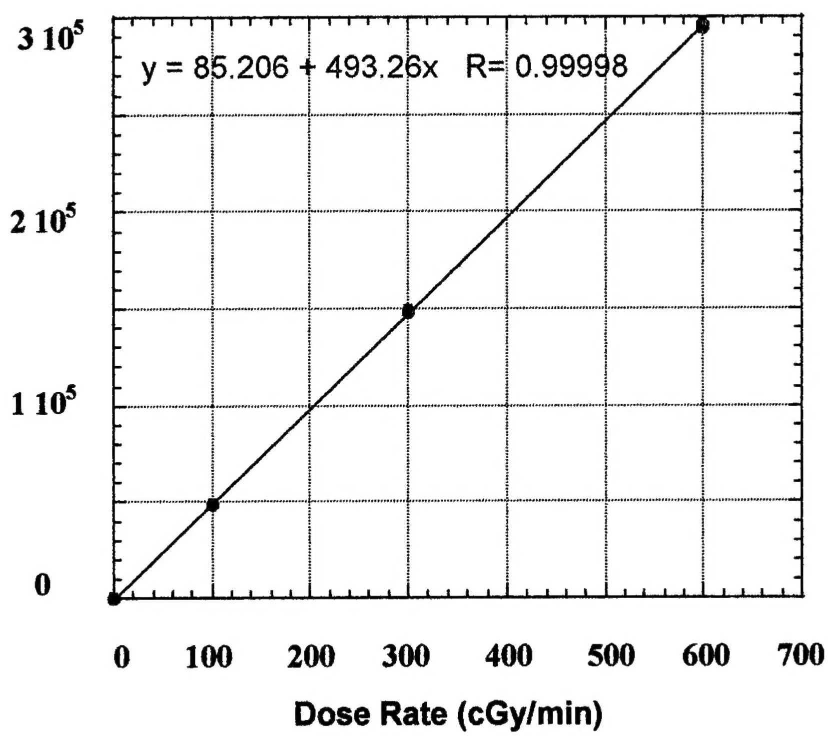

Figure 5. Dose rate measurement using real-time scintillation mode for dose rates of 100, 300 and 600 cGy/min.

Dose Rate Response:

Measurements were performed to determine the dose rate response of the fiber-coupled dosimeter. Figure 5 shows plots of the intensity of the x-ray induced scintillation signal for dose rates of 100cGy/min, 300 cGy/min and 600 cGy/min and the optically stimulated luminescence signals obtained after an accumulated dose of 180 cGy. The plots clearly

show that the intensity of the scintillation signal is proportional to the dose rate and that the OSL signal is independent of dose rate.

Dose Response:

Dose response measurements were performed by exposing the dosimeter for various lengths of time using a dose rate of 300 cGy/min. Figure 6 shows the dose response curves obtained from scintillation and OSL measurements. The dose determination using the scintillation mode was obtained by integrating the signal during the exposure. The OSL measured dose was obtained by integrating the first 20 seconds following laser turn-on. Both plots exhibit linear behavior over the range from 10 cGy to 10,000 cGy. The max deviation from linearity for the largest accumulated dose is about 4%.

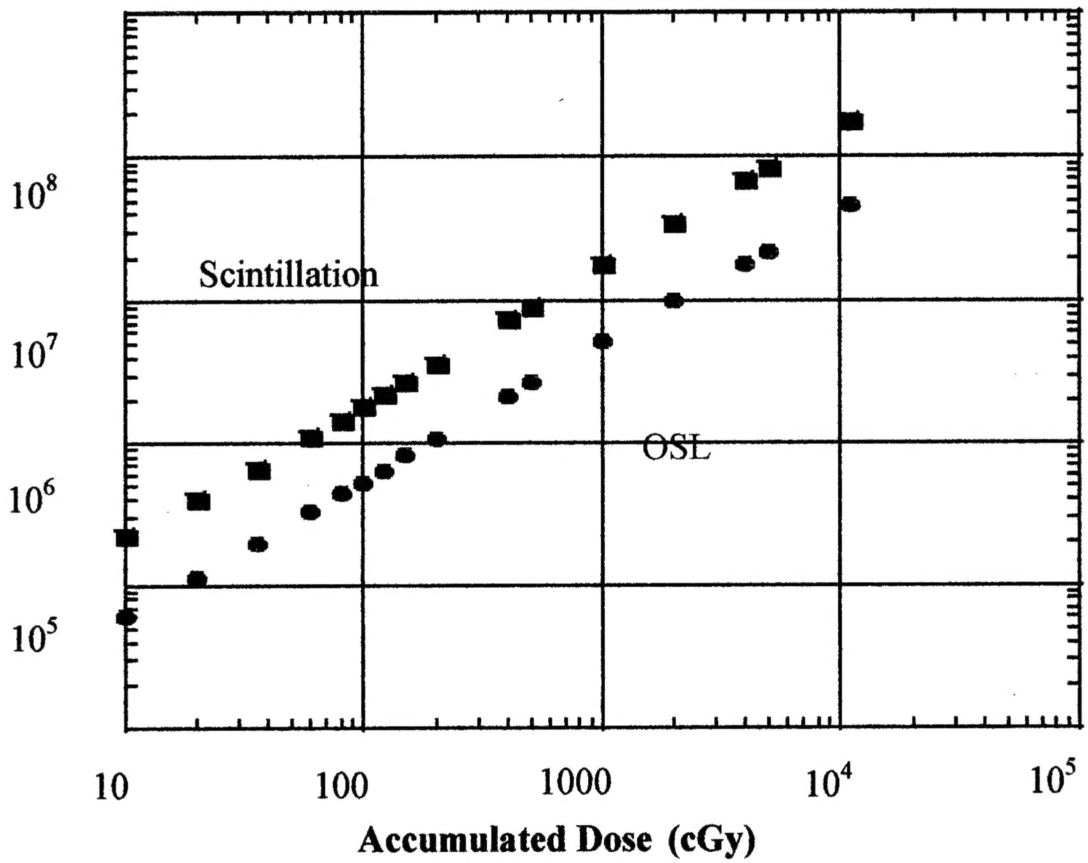

Figure 6. Dose response plots for the fiber-coupled dosimeter displaying the accumulated dose using both the real-time scintillation method and OSL.

The reproducibility of the dose measurements over the range from 1 cGy to 1000 cGy using the scintillation mode is illustrated in Figure 7. Ten measurements obtained at each dose level yielded a standard deviation of $\pm$2%.

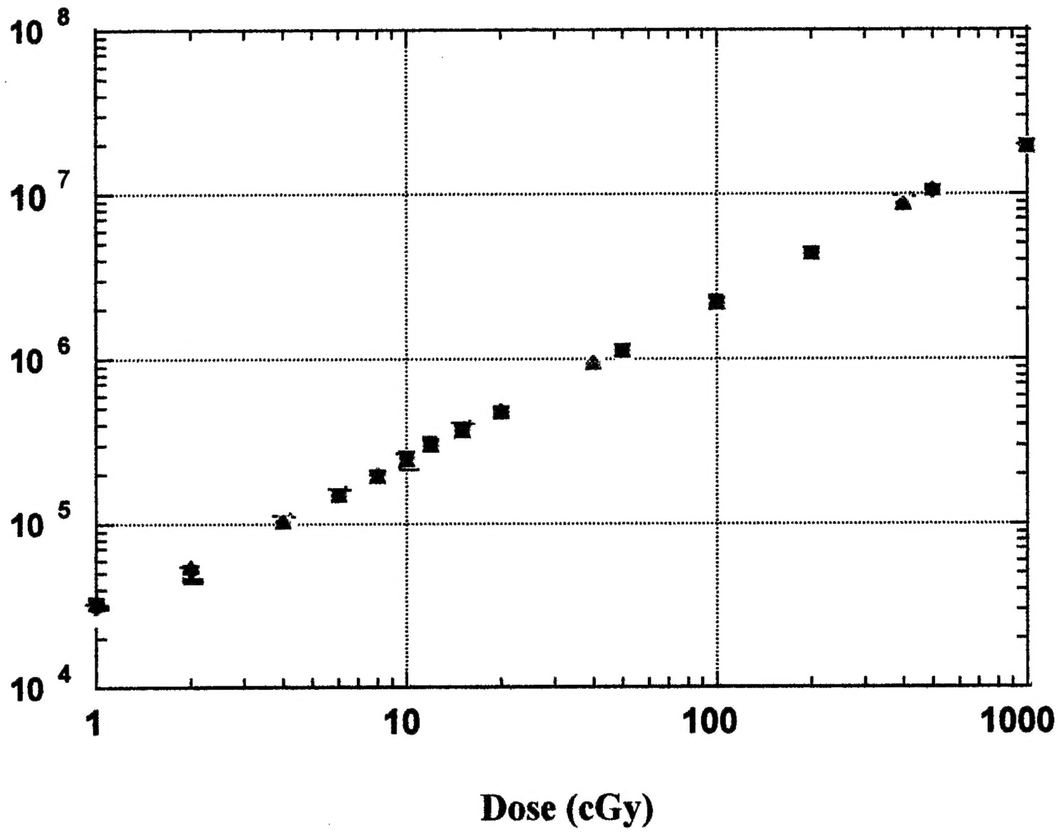

Figure 7. Reproducibility of the dose response. Each point corresponds to 10 separate measurements.

Key Research Accomplishments:

- Produced long lengths of high quality copper-doped glass fiber
- Developed clinically viable multi-channel fiber dosimeter unit
- Developed LabView-based software to control dosimeter
- Developed optical readout unit utilizing fiber bundle technology
- Demonstrated excellent sensitivity for clinical applications
- Demonstrated excellent linearity of response
- Demonstrated excellent reproducibility

Reportable Outcomes:

During the present reporting period there were three presentations, including two invited presentations as listed below:

A.L. Huston and B.L. Justus, "Recent developments in Optically Stimulated Luminescence Dosimetry at the Naval Research laboratory" 17th Annual Panasonic TLD Users Symposium, **Invited** 8-12 June 1998 Santa Rosa, CA.

A.L. Huston and B.L. Justus, "In vivo radiotherapy dose monitoring system", OFS 13th International Conference on Optical Fiber Sensors, **Contributed**, 12-16 April 1999 Kyongju, Korea.

A.L. Huston, "Fiber optic dosimeter for in vivo radiotherapy procedures", **Invited**, 28 September 1999. Georgetown University Medical Center.

We are engaged in licensing negotiations with two large, international corporations that are interested in developing the fiber-coupled dosimeter into a commercial product. The negotiations are being handled by the NRL Technology Transfer Office.

Conclusions:

During this first year of support by the USAMRMC we have made outstanding progress toward the development of a clinically viable, real-time, in vivo radiation dosimeter for monitoring radiation doses during prostate cancer treatments. We have demonstrated very good measurement sensitivity using a small size (<1mm long, 0.4mm diameter) probe attached to a flexible fiberoptic cable. The probe is suitable for use with medical catheters for monitoring radiation treatments directly at the target site. The fiber dosimeter has very good linearity and reproducibility for typical dose levels that are encountered in clinical situations. The probes can be used many hundreds of times with very little change in sensitivity. The dosimeter system should provide a high performance, low-cost method for providing radiation dose information to physicians during radiotherapy treatments that will allow for modifications to the treatment plan in real-time. As a result, the quality of radiotherapy treatments will be improved and the occurrence of adverse side effects will be reduced.

References:

Several manuscripts are in various stages of completion but none have been submitted at this time.

Appendices:
None.